Expectations on Beam Loss in the 400 MeV Linac: Normal Operation, Mis-tuning, & Failure Modes

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Abstract

Beam losses during routine operation of the 400 MeV upgrade linac will depend strongly on the low intensity halo surrounding the 116 MeV beam from tank five of the drift tube linac. The halo can not now be measured at the 116 MeV point, but the use of 200 MeV measurements to set an upper limit is justified by the absence of significant beam loss between 10 and 200 MeV. Operating losses are projected by combining extensive information on the the expectation for beam centroid displacement with the adopted halo model. A discussion is given discounting the need for detailed calculations of the loss patterns corresponding to the multitude of particular conditions associated with tune-up or small mis-adjustments. The characteristic failure modes are identified, and the resulting loss patterns obtained by particle tracking calculations are summarized.

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Introduction

This note draws on measurements of the properties of the 200 MeV beam in the present linac[1] and simulation studies of the 400 MeV upgrade[2] to characterize expected beam loss in the regimes of routine operation, out of tolerance setting and tuning, and component failure. There is an effort to combine a manageable number of representative calculations with some simple ideas on loss management to provide a basis for shielding and interlock design.

Losses in normal operation will depend almost entirely on the halo surrounding the 116 MeV beam from tank five of the present linac, because parameters within the design tolerances do not cause losses from the nominal beam. Losses in the case of component failure, on the contrary, depend only slightly on the initial beam phasespace, but strongly on the beam optics in all three of the orthogonal planes. From one point of view the intermediate regime of tuning or small inadvertent mis-setting is the most difficult to characterize because the rate at which losses increase as a function of small setting errors depends jointly on the beam phasespace and the beam optics of the particular mis-tuned system. However, as a practical matter, it is reasonable to avoid tedious calculations of particular cases by invoking an appropriate policy on loss management. I have in mind three simple ideas, probably suitable as part of such a policy, which can be realized reasonably well in control software or interlock hardware.

By requiring that all tuning procedures be initiated at low dose (intensity and rep rate) and brought up to full intensity only when all parameters are within a few times their design tolerance one avoids long periods with wayward beam at full intensity. Furthermore, it is possible and generally desirable to program routine tuning procedures for the control system in the manner, for example, of the switchyard beam steering programs. These procedures then will generally proceed with a minimum of lost time and misdirected beam. Finally it is a good idea to set radiation trips *reasonably* (note emphasis) close to operating levels even when looser tolerances could be justified on activation or exposure bases. Then the radiation monitor system acts to keep the machine from drifting into settings for which unanticipated loss patterns could occur. Excessive trip frequency leads to significant downtime and unconstructive attitude on the part of some operators, but an occasional trip keeps the crew aware of the machine and encourages them to maintain optimum operation.

If some such policy is followed, normal operation and a few types of component failure make up the relevant sample of specific cases for beam loss analysis. This report first discusses a beam halo model used to asses routine beam loss. Then calculations incorporating distributions of component error within design tolerance are described. Finally tracking calculations for generic failure modes are described and summarized. A few conclusions and recommendations are offered, but detail is presented to help those with the responsibility for radiation safety and interlocks to arrive at their own interpretation.

116 MeV Beam Halo

The radius of DTL tank 5 aperture is 2.0 cm whereas the SC linac has a 1.5 cm aperture throughout the rf structure. Therefore, although there is little loss beyond tank 1 of the DTL, the upgrade design has anticipated a loss of about one percent. The transverse plane normalized emittances for 95 % of the beam are about 6.8π mm mrad. This emittance is six times the rms emittance if the distribution is treated as Gaussian. The beam envelope calculations for the upgrade use these emittance values, although they are considered there as $5\varepsilon_{rms}$ for the space charge calculations. The maximum width of the envelope of this "core beam" is 1.04 cm.

We use two halo models based on the measurements which appear to bracket the actual situation between them. One model is a truncated Gaussian containing 95 % of the beam within 6.8π emittance. The remaining 5 % is included in a nearly Gaussian tail modified so that it goes to a true zero at 13.6π, the $12\varepsilon_{rms}$ point for a Gaussian. A model which enhances the extreme tail in comparison to either a Gaussian or the observations consists of a 6.8π waterbag containing 95 % of the beam combined with a 13.6π waterbag containing 5 % between 6.8π and 13.6π. Loss runs for the nominal upgrade linac have been made with both models.

The maximum envelope widths are thus 1.04 cm for the core and 1.48 cm for the halo, so it looks as though even the halo should squeak through. However, clean passage of the halo can only be obtained in the linear optics approximation of the envelope calculation. When the non-linear effects are included by using the particle tracking code, the loss is about 0.8 % for the truncated Gaussian with losses in modules 1 – 4 but no more than 0.4 % lost in one module. The double waterbag model beam suffers a loss of about 1.4 % with nearly 1 % in module 1 and some loss downstream to module 5. These losses tend to concentrate at the ends of rf tanks adjacent to the quads because the quads themselves have an aperture of about 1.75 cm inside a 1.5 in o.d. beampipe.

One open question raised in the conceptual design has yet to be thoroughly considered. It is suggested that it could be advantageous to localize the losses by a $\sim 1\%$ scraper, perhaps located in the transition section. Another possibility might be in association with the NTF target area since that is already a hot spot. Scraping of this order should avoid nearly all losses at higher energy in routine operation.

Losses Attributable to Errors Within Tolerance

Thorough studies of error tolerance show that there are *no* losses from the core beam arising from distributions of quad and cavity strength within design tolerance or from random misalignment within the specification of 0.1 mm that applies within a module. The tolerance specification for girder-to-girder misalignment is 1.0 mm; the correlated displacement of sets of components on this scale gives no more than a statistical assurance of high probability that some of the beam can make it all the way through without steering corrections. Certainly steering will be required to achieve acceptable losses. The specified steering coils and beam position monitors can achieve zero loss for the core beam.

There has not been a series of tracking runs with halo for a representative ensemble of parameter error distributions. However, combining the beam halo size with comprehensive results for expectation values for the beam centroid indicates that one should be prepared for losses of $\sim 2\%$ but work toward a target of better than 1 %. Loss at about the 1 % level is almost unavoidable at some place along the line on the basis of present beam emittance. Such losses will tend to be greatest in the first two modules where the beam envelope is widest, but the envelope shrinks rather slowly with momentum because the effect of the dropping emittance is partly offset by weaker focussing. Because the spacing between steering correctors also increases with momentum, it seems prudent to provide shielding for the possibility of operation with a steady 2 % loss in any module. From the point of view of residual activity this is more than one should tolerate indefinitely, but a more restrictive limit without a time exception could be an obstacle to progress in early performance.

Component Failures

The kind of abnormal condition one can expect with some frequency is the complete failure of a single component. The failure might consist of a total absence of function, a power supply going to full output, or, in the case of steering elements, a power supply with the wrong polarity. The components to be considered are the focusing quads, the klystrons, and the steering magnets. According to the reasoning of Schmidt[3], the tripping of a klystron power supply can provide a trigger to terminate the beam pulse within a few microseconds by using the 750 keV chopper. Because this period is comparable to the fill time of the rf structure, the beam should be gone before the cavity gradient is fully down. For the purpose of characterizing the spacial pattern of the losses when a klystron power supply trips we have tracked to find where the beam ends up when each of the seven accelerating klystron outputs is separately set to zero. The duration which one wishes to associate with such loss patterns depends on the assessment of the reliability of the Booster off-chopper firing line connection to the 750 keV chopper, but even conservatively one need consider only a single full pulse in this failure mode because there are other systems to inhibit beam on a next-pulse basis. For a fault in modules 1 – 3, the loss is practically 100 % with little loss in the affected module or the one next downstream. To a useful approximation the second module downstream can be taken as a uniform source with 100 % of the beam dumped there. This pattern is apparent in the result for a fault in module 2 shown in Fig. 2. The pattern is qualitatively distinct for failures in modules 4 – 7. Much or all of the beam survives with 15 % loss for a module 4 failure and $< 5\%$ loss for later ones. The beam exiting the linac has the wrong energy, of course, and will be lost in the 400 MeV diagnostic area and the chute to Booster level.

The loss pattern resulting from a quad power supply trip is more localized. The total loss ranges from about 70 % for a quad near the beginning of the linac to about 50 % for one near the end. About 20 % of the loss occurs near the second quad downstream and about 80 % occurs near the third downstream quad. This pattern is shown in Fig. 3 for the quad in the middle of module 1. Turning the beam off because of a quad trip will presumably be accomplished on the next pulse by the beam loss monitoring system. This can be backed up by an inhibit based on computer checks of the readback of all supplies. However, a supply only slightly out of tolerance should probably cause an alarm without inhibiting beam.

Although the steering coils are designed for only about a milliradian, energizing one at the wrong polarity can result in angular kick of up to two milliradian from the corrected trajectory. With a lever arm of ~ 2 m to the next quad this error will be somewhat worse than a displacement of the quad center by 4 mm since the angle error remains. The next quad will be defocusing in the plane of deflection and will amplify the angle error by about a factor of two; thus, by the time one reaches a focusing quad the closed orbit amplitude can be ~ 1 cm. For the worse case of a reversed steering coil producing a 2 mrad kick the loss can approach 100 % of the beam. The example shown in Fig. 4 is for the steering coil under the last bridge in module 4. The loss for this case is 72 % and occurs almost entirely at the next quad focusing in the deflection plane. Losses are slightly lower for failures upstream and slightly higher for downstream failures because of the greater space between focusing elements at higher energy. The more likely case of a power supply simply being off and taking a worst case deflection of 1 mrad leads to a loss of only about 5 % with a similar localization. A more typical trip with the element running near mid-range will result in perhaps a factor two increase above normal operating loss. It is apparent that we should avoid installing more steering capability than reasonably required at each location; therefore, since power supplies will presumably be standard, we may want to have more different sizes of steering coil.

Conclusions/Recommendations

Hereafter follow summary generalities and some suggestions for suitable response to the perceived sources and magnitudes of beam loss in the 400 MeV linac upstream of the diagnostic area. To assist in evaluating the problems further downstream, the linac upgrade group can provide samples of 400 MeV beam particle coordinates corresponding to normal operation or any particular failure mode desired for use with TURTLE or other beamline tracking program. We conclude in general

1. The policy on losses during normal operation has important bearing on the types of malfunction that must be considered as relevant causes of beam loss for evaluation of beam activation and protective interlocks. It is probable that a reasonable policy can be formulated which requires detailed calculation of a practicable number particular cases.

2. The 116 MeV halo has particular significance for loss during routine operation. On the basis of 200 MeV measurements a loss of ~ 1 %, either intentionally localized or accepted over the first four modules or so, is practically unavoidable.

3. The loss permitted in routine operation should be about 2 % max with administrative guidance toward a level of better than 1 %.

4. The three basic failure modes are

    - klystron crowbar resulting from a spark in a tank, occurring on about 0.1 % of pulses during operation,

- quad power supply trip,
- steering element power supply trip or wrong polarity.

5. Though specific loss patterns differ, it is certainly possible to lose nearly all of the beam near the end of a tank or to spread losses large or small over two or more modules. For worst case analysis one should consider four basic patterns:

   - practically full loss at the end of an rf tank
   - full loss uniform over one module
   - beam at $\sim$ 360 MeV arriving at end of linac with about the usual transverse phase space
   - full-aperture 400 MeV beam ($\varepsilon \approx 22.5\pi$mm mrad) arriving at end of linac, about three times normal emittance

References

[1] C. Schmidt, beam measurements 1 Aug 89, priv. comm.

[2] L. Oleksiuk, calculations with his CAVDYN program, see LU - 157, Fermilab linac upgrade note(Jan 90), unpublished

[3] C. Schmidt, "Linac Beam and Equipment Interlocks", draft note(16 July 90)

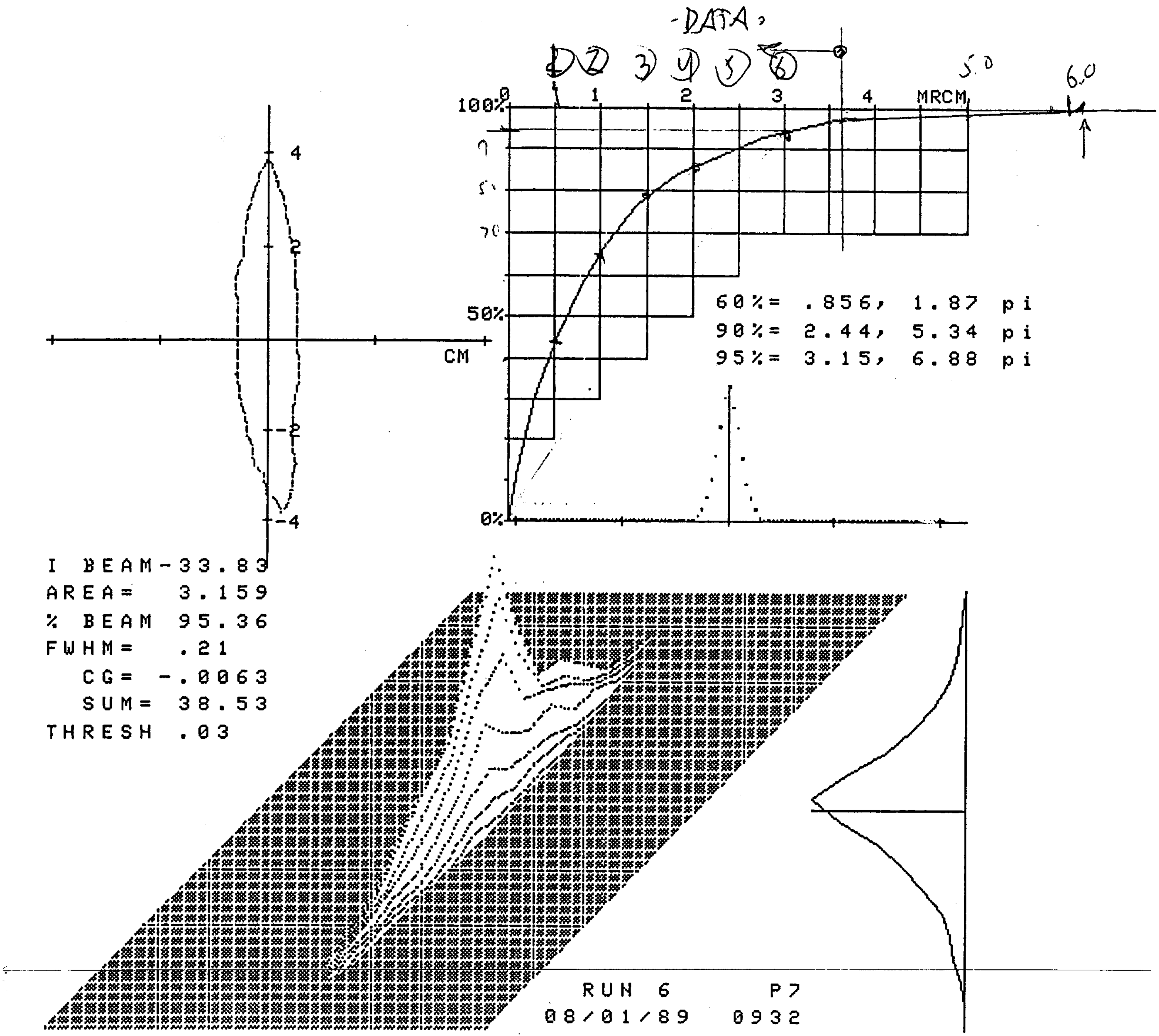

Figure 1: Horizontal emittance data at 200 MeV

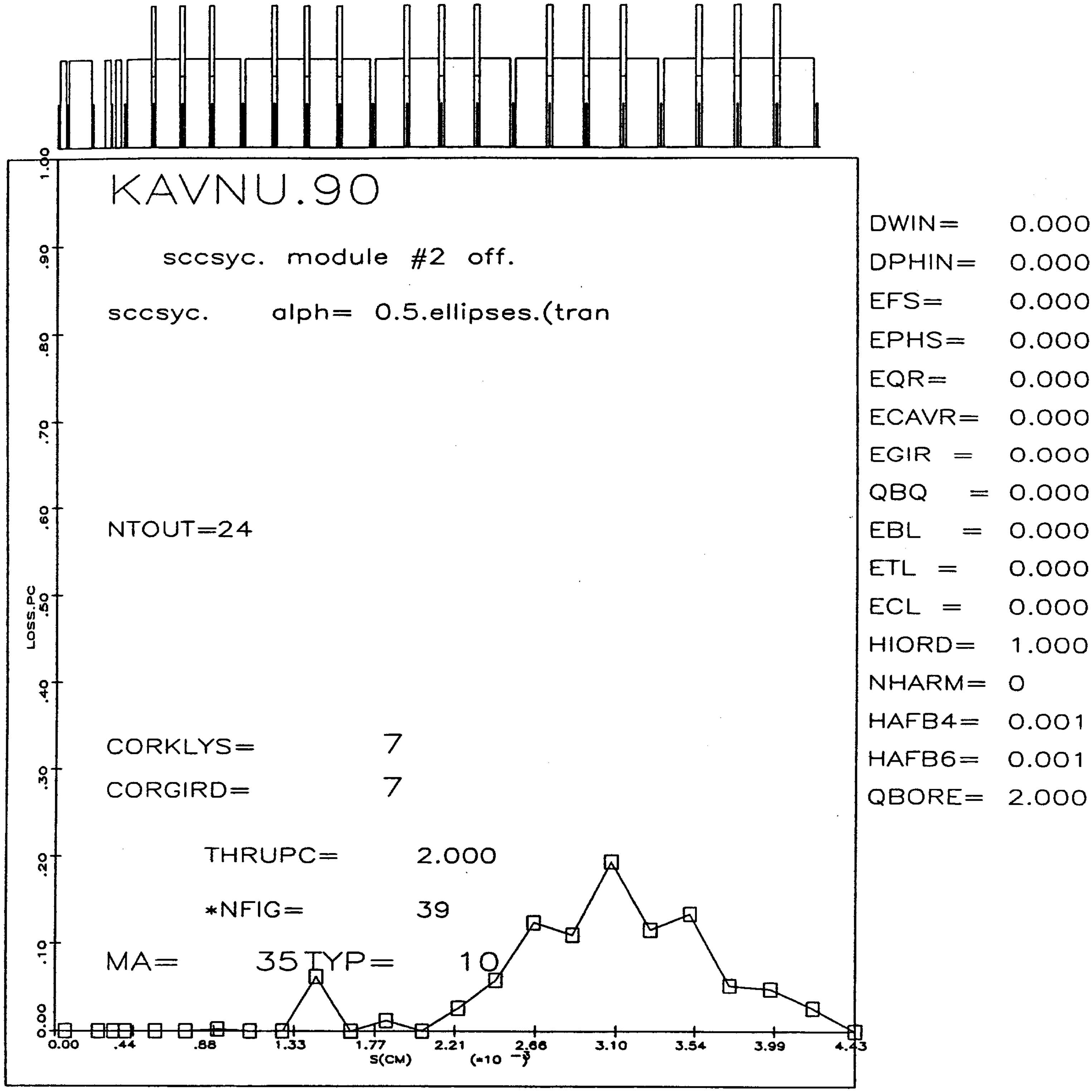

Figure 2: Beam loss resulting from trip of klystron in module 2

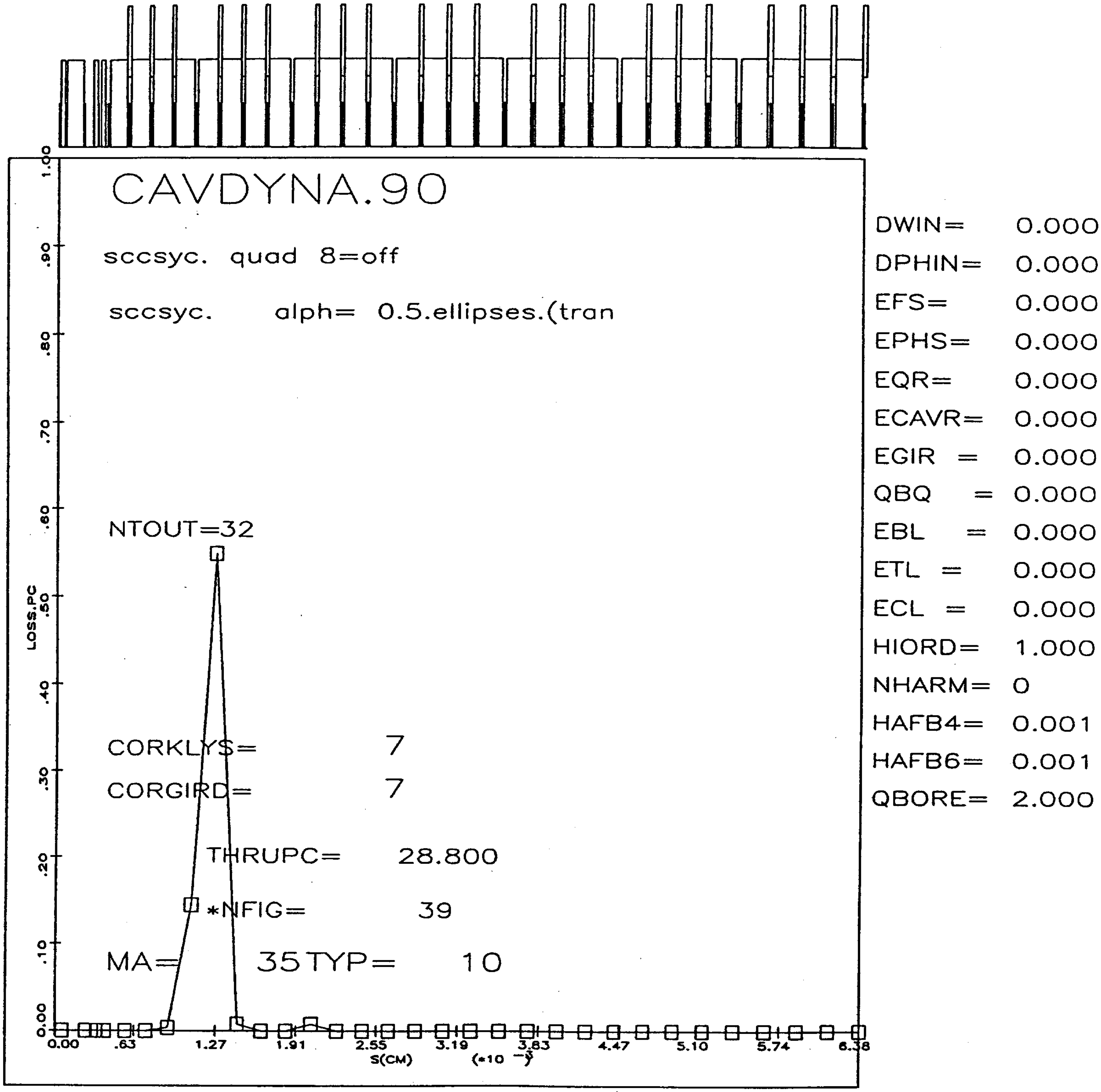

Figure 3: Beam loss from quad off at middle of module 1 calculated by particle tracking progam CAVDYN

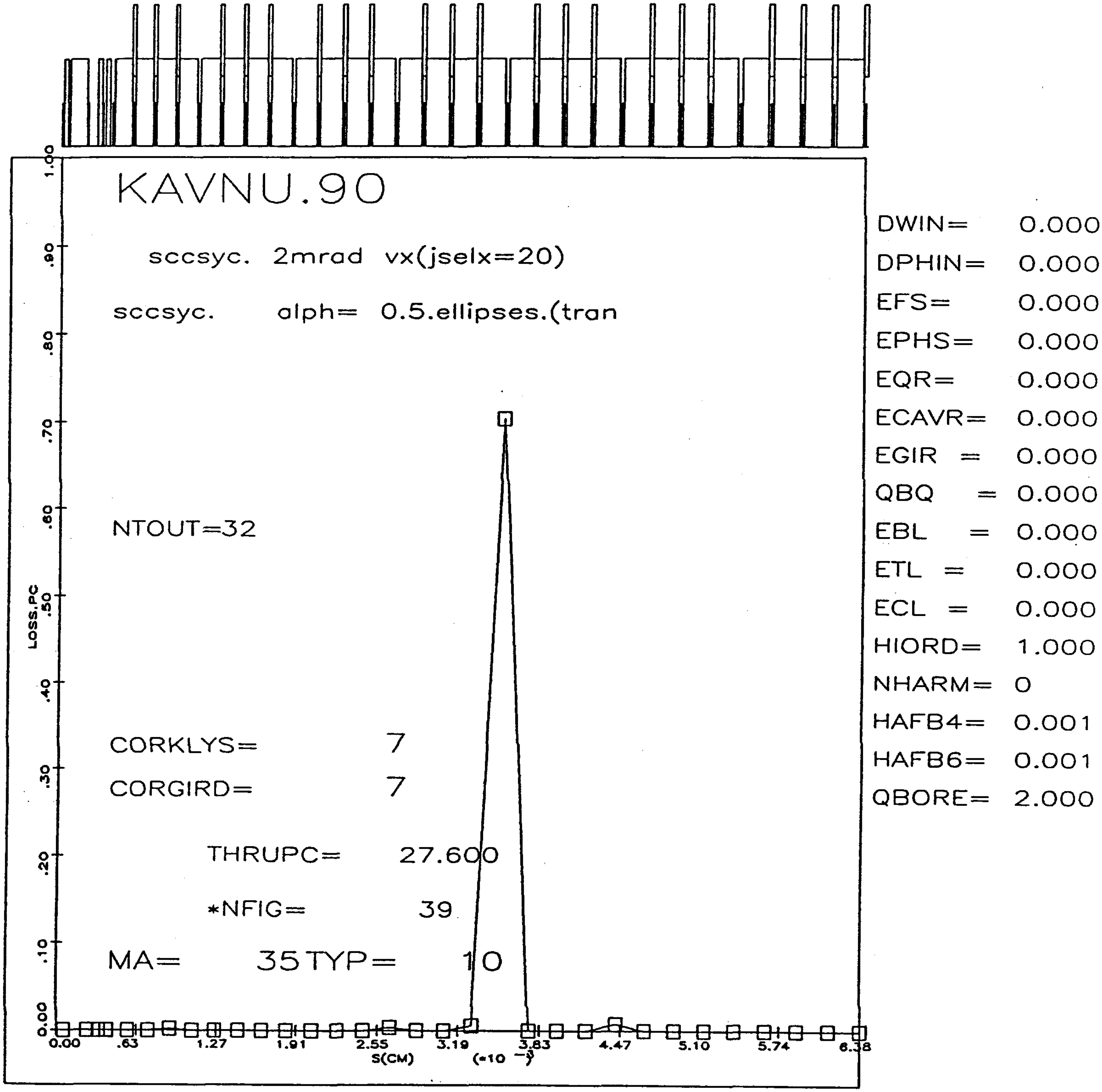

Figure 4: Beam loss resulting from wrong polarity of full-on horizontal steering coil at end of module 4